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Long-term alterations of flow regimes of the Mekong River and adaptation strategies for the Vietnamese Mekong Delta

Doan Van Binh [a,b,*], Sameh A. Kantoush [a], Mohamed Saber [a], Nguyen Phuong Mai [c], Shreedhar Maskey [d], Dang Tuan Phong [c], Tetsuya Sumi [a]

[a] *Water Resources Center, Disaster Prevention Research Institute, Kyoto University, Goka-sho, Uji City, Kyoto, 611-0011, Japan*
[b] *Department of Water Resources Engineering, Thuyloi University, 175 Tay Son, Dong Da, Hanoi, Viet Nam*
[c] *Department of Civil Engineering, Thuyloi University, 175 Tay Son, Dong Da, Hanoi, Viet Nam*
[d] *IHE Delft Institute for Water Education, P.O. Box 3015, 2601 DA, Delft, the Netherlands*

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ABSTRACT

Study region: The Mekong basin, where climate change and anthropogenic interventions (e.g., dams, sand mining, and sluice gates) have intensified in the recent decades affecting the pristine flow regime and salinity intrusion.

Study focus: This paper aims at quantifying the flow regime alterations in the entire Mekong from 1980 to 2015 and linking with the controlling drivers of alterations. In this regard, various indicators, analytical methods, and a semi two-dimensional hydrodynamic and advection-dispersion model were used.

New hydrological insights for the region: The flow regime alterations in the high-dam development period (2009–2015) are more pronounced than in the low-dam development period (1993–2008), compared to the no-dam development period (1980–1992), based on most of the indicators analyzed. In the high-dam development period all existing dams with large reservoir capacity seemed to have cumulatively reduced the flood pulses and frequency and increased the low-flow discharge along the entire Mekong through reservoir operations, exceeding climate change effect. In the recent years the water levels in the low-flow season in the Vietnamese Mekong Delta (VMD) have decreased, possibly because of increased riverbed incision caused by reduced sediment supply and increased sand mining. The reduced water levels together with the increased number of the sluice gates constructed seemed to have increased salinity intrusion in the VMD which may be partly reduced by early emergency water release from upstream dams.

1. Introduction

Natural river flow regimes produce spatial and temporal variations in environmental conditions, which are crucial to support native biodiversity and the integrity of riverine ecosystems (Poff and Ward, 1989; Richter et al., 1998). Flood pulse is the primary

* Corresponding author at: Water Resources Center, Disaster Prevention Research Institute, Kyoto University, Goka-sho, Uji City, Kyoto, 611-0011, Japan.

E-mail addresses: doan.binhvan.3e@kyoto-u.ac.jp, binhdv@tlu.edu.vn (D.V. Binh), kantoush.samehahmed.2n@kyoto-u.ac.jp (S.A. Kantoush), mohamedmd.saber.3u@kyoto-u.ac.jp (M. Saber), maiswru@tlu.edu.vn (N.P. Mai), s.maskey@un-ihe.org (S. Maskey), phongdt@tlu.edu.vn (D.T. Phong), sumi.tetsuya.2s@kyoto-u.ac.jp (T. Sumi).

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driving forces for the productivity of ecosystems in the Mekong River (the Mekong) basin (Räsänen et al., 2017). The longitudinal connectivity and dynamic flow variability between the Mekong and its floodplains are needed for sustaining fish migration and promoting the exchange of water, sediment, and nutrients. In this regard, the Tonle Sap Lake plays an important role as a natural

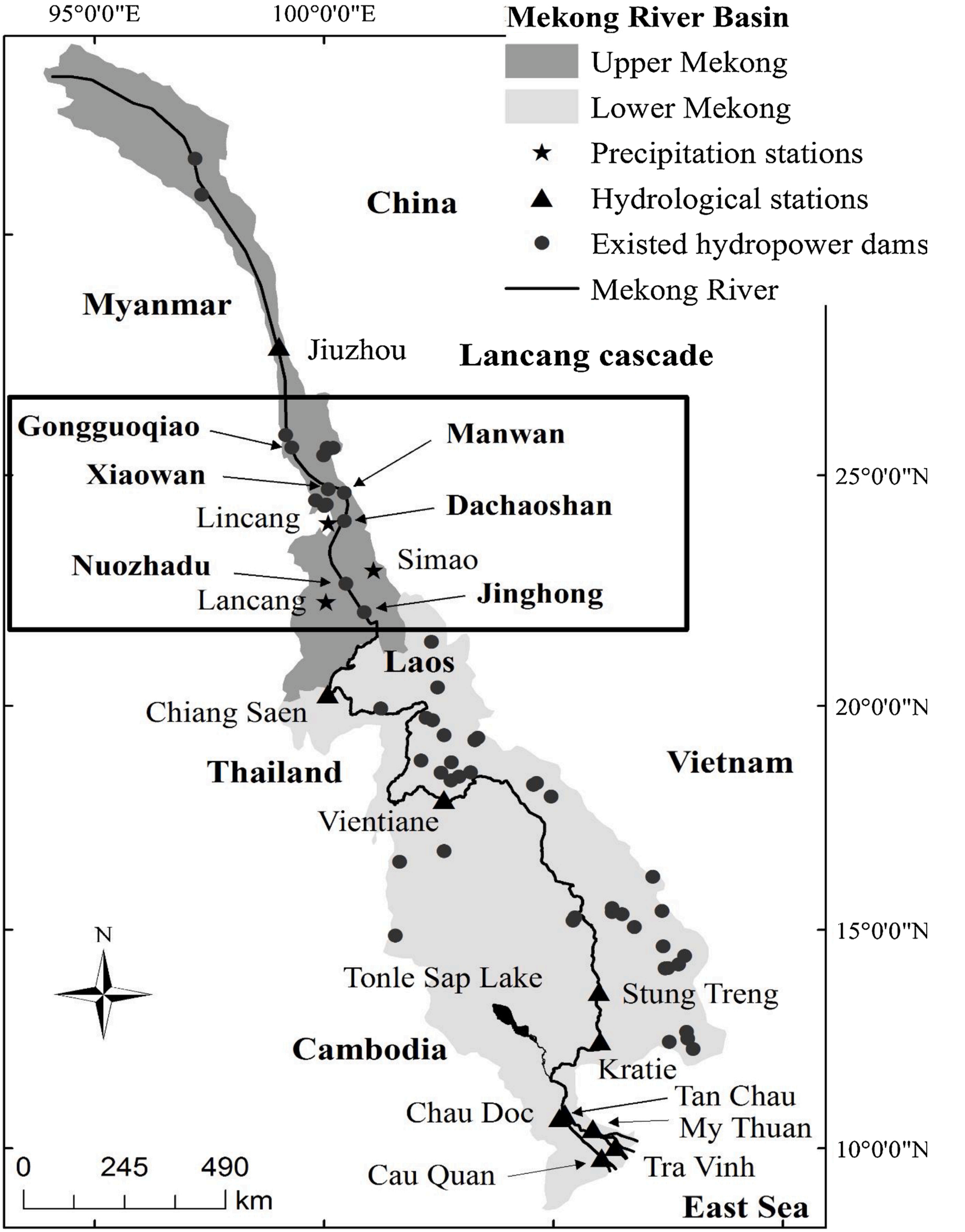

Fig. 1. Map of Mekong basin: locations of existing dams, rain gauges, and hydrological stations.

reservoir to regulate the flood pulse of its downstream floodplains in Cambodia and Vietnam by receiving flows from the upstream reaches during high-flow periods and releasing water back to the Mekong during low-flow periods (Pokhrel et al., 2018).

However, increased socioeconomic development of the recent decades has led to the construction of hydropower dams, weirs, and reservoirs for multi-purposes, water diversions for irrigation and navigation, and sluice gates for flow and salinity control (Yin et al., 2015). In the Mekong basin, >130 dams have been built and planned since the 1990s, of which 64 large dams (>15 m high) were completed by 2017 (Hecht et al., 2019) (Fig. 1). The total storage capacity of the 64 existing dams is over 82 km^3 (Table S1), accounting for more than 98 % of the annual discharges at the Chiang Saen station, of which six mega mainstream hydropower dams in the upper Mekong (known as Lancang cascade) constitute approximately 50 % (Table 1). Among the 64 existing dams, 13 dams are in the upper Mekong and another 51 dams are in the tributaries of the lower Mekong basin. These hydraulic infrastructures have significantly altered flow regimes of the Mekong by affecting the quality, quantity, and intra-and-inter-annual variations of the flow regime, such as frequency, timing, and duration of the flood discharges (Lauri et al., 2012; Lu et al., 2014; Manh et al., 2015; Räsänen et al., 2017). Dams normally cut the flood peak and reduce the amplitude of annual flood pulses, causing disconnection between rivers and floodplains. Dams also trap sediment, reducing the sediment volume that can be transported downstream to maintain river channels and coastal landforms (Kondolf et al., 2014; Shrestha et al., 2018). Additionally, dam operations may cause prolonged and earlier salinity intrusion in the Vietnamese Mekong Delta (VMD) (Mai et al., 2018) because of riverbed degradation caused by upstream dam development and sand mining (Binh et al., 2018a, 2020; Eslami et al., 2019). Moreover, fish migration paths are blocked by dams (Pokhrel et al., 2018), leading to losses of biodiversity and degradation of the aquatic and terrestrial ecosystems in the Mekong basin (Arias et al., 2014).

Climate and land use changes are also major drivers that alter the hydrologic regime (Bao et al., 2012; Milliman et al., 2008; Wang et al., 2006) with significant impacts on social and environmental variables. Changing rainfall intensity and patterns induced by climate change could result in changing hydrological circle (Wang et al., 2017). Although climate change is known as one of the drivers of flow alterations, its impacts on flow regime alterations in the Mekong are profusely smaller than those caused by hydropower dams (Arias et al., 2014; Lauri et al., 2012). A similar trend was found in the Yellow River, where the annual runoff decreased by 82 %, although the annual precipitation exhibited only slight changes (Milliman et al., 2008). Additionally, dam-induced flow regime alterations in the Mekong basin far exceed the land use-induced influence (Li et al., 2017).

Understanding long-term alterations of the flow regimes along the Mekong is of crucial importance for evidence based sustainable water management strategies and informed decisions to share benefits from the transboundary Mekong in the coming decades. Any decision from stakeholders based on a short-term flow analysis may lead to unsustainable development. Therefore, the functioning of existing high-dike systems and salinity control sluice gates in the VMD has been heavily debated and revised. Many scientists have argued against these structures because they may worsen the situation (e.g., Triet et al., 2017). High-dike systems may destroy soil properties and wetland ecosystems because nutrient-rich fine sediment blocks access to the wetlands and agriculture areas. Furthermore, salinity control sluice gates may increase the intrusion length up-river because of reduced buffering zones near the estuaries. It may well be that these structures were suitable at the time of being built; however, they may have become a constraint in recent years because of unexpected flow regime alterations that outrange the design values. Therefore, the investigation of long-term flow regime alterations plays a fundamental reference for sustainable water resource management strategies.

Various studies have sought to understand the impacts of dams along the Mekong basin (Binh et al., 2020; Li et al., 2017; Räsänen et al., 2017), and some have worked to adapt and apply adaptive measures to specific areas within the delta or the lower Mekong (Ha et al., 2018a; Smajgl et al., 2015; Triet et al., 2017). However, long-term flow alterations along the entire lower Mekong, especially the VMD, have not been fully understood, which may in turn challenge proposed adaptive measures. In this context, the specific shortcoming of prior studies is the lack of comprehensive assessment that links long-term hydrologic flow regime alterations to the controlling factors and management variables.

The goals of this work are (1) to quantify long-term flow regime alterations along the entire lower Mekong, including the VMD and (2) to link flow regime alterations with the controlling factors, including climate variability and dams. Based on these understanding, we propose possible interventions across various regions in the Mekong basin to improve water and environmental management. The outcomes of this research can be referred by stakeholders to plan strategic river basin management and to make sustainable long-term decisions. One of the unique contributions of our study is providing evidence-based historical changes of the hydrology in the VMD which is important for informing future preparedness and adaptive strategies.

Table 1
Profiles of six commissioned mainstream hydropower dams in the Lancang cascade.

Name	Catchment area (km^2)	Annual inflow (m^3/s)	Dam height (m)	Active storage (km^3)	Total storage (km^3)	Annual generation (GWh)	Started year	Reservoir filling year
Nuozhadu	144,700	1,750	260	12.2	22.37	23,780	2005	Nov. 2011
Xiaowan	113,300	1,220	292	9.9	15.13	18,890	2002	Dec. 2008
Jinghong	149,100	1,840	107	0.25	1.23	8,060	2003	Apr. 2008
Manwan	114,500	1,230	132	0.26	1.06	7,810	1986	Mar. 1993
Daochaoshan	121,000	1,340	120.5	0.37	0.88	6,700	1997	Nov. 2001
Gongguoqiao	97,300	985	130	0.12	0.51	4,060	2008	Sep. 2011
Total				**23.1**	**41.18**	**69,300**		

Source: (Fan et al., 2015; Li et al., 2017).

2. Materials and methods

2.1. Study area

The Mekong is 4880 km long and has a catchment area of 795,000 km^2, running through China, Myanmar, Laos, Thailand, Cambodia, and Vietnam before emptying into the East Sea of Vietnam (Fig. 1). The Mekong basin is spatially divided into the upper Mekong (or the Lancang; 24 % of the total area) and lower Mekong (76 % of the total area). The upper Mekong is widely defined as the area upstream of Chiang Saen, Thailand, and lies mostly in China. It contributes 34 % of the mean annual discharge at Pakse (Kiem et al., 2008) and approximately 18 % of the mean annual flow of the Mekong (Mekong River Commission (MRC, 2005), but up to 75 % and 40 % of the low flows at Vientiane and Kratie, respectively (Adamson et al., 2009). The lower Mekong lies in Thailand, Laos, Cambodia, and Vietnam. Approximately 85–90 % of the Mekong's flow occurs in the wet season (May-October), with an average peak flow of approximately 45,000 m^3/s (Lu and Siew, 2006), controlled by monsoon precipitation and the flow from the left-bank tributaries in Laos and Vietnam (Cook et al., 2012). The remaining 10–15 % of the river flow takes place in the dry season (November-April), with an average minimum discharge of approximately 1500 m^3/s, controlled by the flow from snow melt in the upper Mekong.

Located in the lowermost of the Mekong, the VMD is home to approximately 17 million people whose livelihoods are dependent on agriculture and aquaculture. The VMD is a low-lying area, having an average ground elevation of 0.7–1.2 m. The total area of the VMD is approximately 39,000 km^2, from the Vietnam-Cambodia border, several kilometers upstream of the Tan Chau and Chau Doc gauging stations, to the East and West Seas of Vietnam (Fig. 1). There are two main waterways in the VMD: the Tien and Hau rivers (Vietnamese names of the Mekong and Bassac rivers). The Tien river conveys approximately 80 % of the flow, and the Hau river transports approximately 20 %. The flood season in the VMD extends from June/July to November/December, while the dry season lasts for nearly half the year from November/December to May/June.

The VMD is one of the most vulnerable deltas in the world regarding salinity intrusion accompanied by sea level rise and upstream development (Smajgl et al., 2015). There have been growing concerns of the potential impacts of salinity intrusion and changes in seasonal water availability on the VMD rice production as a result of climate change, land use change and infrastructure developments (Hoang et al., 2016). Annually, water with a salinity concentration of 4 g/l intrudes approximately 40−50 km inland in March-April, affecting 1.4–1.7 million hectares (Toan, 2014). The intrusion length might be 20−25 km further than usual under severe drought events, i.e., in the 2015–2016 drought year (Kantoush et al., 2017).

2.2. Data collection and missing data estimation

The analysis of flow regime alterations was performed based on daily discharges and water levels measured at Chiang Saen, Kratie, Tan Chau, Chau Doc, and My Thuan over 36 years (1980–2015), and monthly maximum salinity concentrations at Tra Vinh and Cau Quan measured during the period 1990–2016 (Fig. 1). These data were provided by the Vietnamese National Hydro-meteorological Data Centre and the Mekong River Commission (MRC). Because Chiang Saen is located just downstream of the Lancang cascade, changes in the flow regimes at this station largely reflect the influence of dam operations in the cascade. Differences in the flow patterns between Chiang Saen and Kratie are likely attributed to the contribution of tributaries, mainly in Thailand and Laos.

Daily water levels at Tan Chau and Chau Doc in the VMD were continuously measured from 1980 to 2015 while daily discharges were available from 1996 to 2015. From 1980–1995, daily discharges at these two stations were measured some months a year, in both flood and dry seasons. Therefore, we developed rating curves to estimate the missing discharges based on all available daily data at each station. The developed rating curves were generated for the rising (April-September) and falling (October-March) stages separately using polynomial regression with the least squares method. The rating equations for the rising and falling stages at Tan Chau are exhibited by Eqs. (1) and (2), respectively, while the respective equations at Chau Doc are given in Eqs. (3) and (4):

$$Q = -0.0913Z^2 + 92.433Z - 1060.7 \quad (1)$$

$$Q = -0.0592Z^2 + 77.11Z - 1643.7 \quad (2)$$

$$Q = -0.0174Z^2 + 25.32Z - 484.5 \quad (3)$$

$$Q = -0.0075Z^2 + 24.531Z - 796.9 \quad (4)$$

where Q is the discharge (in m^3/s), and Z is the water level (in cm). Missing discharges were well predicted by these equations with high coefficients of determination, R^2 (0.95–0.96). Fig. S1 shows that the 95 % confidence interval lines cover most of the input data although some extreme values were over- or under-estimated.

All daily discharges at all stations during the period 1980–2015 were classified into the high-flow (discharge ≥25th percentile), the transition-flow (discharge between the 25th and 75th percentiles), and the low-flow (discharges ≤75th percentile), as shown in Table S2. In general, the high-flow season upstream of the VMD starts one month earlier, and the low-flow season at such locations ends one month earlier than those within the VMD. The high-flow transports a majority of the annual flow, e.g., 62 % at Chiang Saen and 74 % at Kratie.

2.3. Precipitation datasets

In many regions over the world, it is well known that the rain gauges are sparsely distributed with very limited long-term records. Therefore, using gridded global data products, such as globally or regionally interpolated from observation, reanalysis and satellite-based precipitation datasets, is a promising alternative specially in the Mekong basin. To understand the spatial and temporal variability of the precipitation, as an indication of climatic impacts on the flow regimes over the Mekong basin, from 1980 to 2015, we employed three precipitation datasets, including the Climate Research Unit (CRU TS 4.03), the Global Precipitation Climatology Center (GPCC), and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Network–Climate Data Record (PERSIANN–CDR). The CRU dataset was developed by the UK's National Centre for Atmospheric Science (NCAS) at the University of East Anglia's Climatic Research Unit, based on the observational data. The datasets are monthly available on a spatial resolution of 0.5° × 0.5°, covering the globe from 1901 to 2018 (Harris et al., 2020). In this study, the version 2018 of GPCC dataset with a spatial resolution of 0.5° × 0.5° was used. It is monthly land-surface precipitation from rain-gauges built on GTS-based and historical data, and available from 1891 to 2016 with different spatial resolutions (Schneider et al., 2018). The PERSIANN–CDR satellite-based dataset is daily available from 1983 to 2018 on a spatial resolution of 0.25° × 0.25° (Ashouri et al., 2015). These datasets were used because of their long-term availability and fine spatial resolutions. We first compared these three datasets with some of the existing rain gauges in the Mekong basin and found that the CRU data performed better than GPCC and PERSIANN-CDR data (Fig. S2). Additionally, the CRU datasets were used as reference of observational data in comparison with many other precipitation and climatic datasets (e.g., Ayugi et al., 2020). Therefore, the basin-scale CRU data were used to perform the long-term variations of the precipitation in this study.

2.4. Methods

2.4.1. Impact assessment of flow regime metrics

The first large dam in the Mekong basin, Manwan, was operated in 1993. Therefore, the long-term flow was divided into the NDD period (no dam development, 1980–1992) and the postdam period (1993–2015) to assess dam impacts. This division was commonly considered in previous studies (e.g., Lauri et al., 2012; Lu and Siew, 2006). The discrepancies of the twenty-one flow regime metrics (Table 2) between the NDD and postdam periods were quantified. The absolute discrepancy was used for the impact assessment of the timing, and the relative discrepancy was used for the impact assessment of the magnitude, duration, and frequency. The equations of the absolute and relative discrepancies were adopted based on Zhang et al. (2018), as follows:

$$\begin{aligned} AD^i &= V^i_{post} - \overline{V}^i_{pre} \\ RD^i &= AD^i \Big/ \overline{V}^i_{pre} * 100\% \\ \overline{V}^i_{pre} &= \sum_1^N V^i_{pre} \Big/ N \end{aligned} \tag{5}$$

where AD^i and RD^i are the absolute and relative discrepancies of the ith metric, respectively; V^i_{pre} and V^i_{post} are the values in the NDD and postdam periods of the ith metric, respectively; $\overline{V}^i_{pre}$ is mean value in the NDD period of the ith metric; and N is the number of years in the NDD period. If the discrepancy is greater than 0, the flow regime metrics are positively impacted; if it is equal to 0, no impact is detected; and if it is less than 0, the flow regime metrics are negatively impacted. Then, the relative discrepancy was categorized into five grades based on the percentiles as adopted from Zhang et al. (2018): no impact ($-5\ \% \le RD \le 5\ \%$), slight ($-15\ \% \le RD < -5\ \%$ or $5\ \% < RD \le 15\ \%$), moderate ($-30\ \% \le RD < -15\ \%$ or $15\ \% < RD \le 30\ \%$), high ($-45\ \% \le RD < -30\ \%$ or $30\ \% < RD \le 45\ \%$), and extreme ($RD < -45\ \%$ or $45\ \% < RD$).

Table 2
Flow regime metrics used in impact assessment of long-term hydrologic alterations.

Groups	Regime characteristics	Hydrologic metrics	Unit
Magnitude	Average flow	- Mean daily discharge of each month during transition-flow period - Mean daily discharge of a year - Discharges in 40 and 60 percentiles of the FDC: Q40 and Q60	m^3/s
	High-flow	- Mean daily discharge of each month during high-flow period - Annual 1-day maximum discharge - Extreme high-flow discharge Q10 (10 percentiles of the FDC)	m^3/s
	Low-flow	- Mean daily discharge of each month during low-flow period - Annual 1-day minimum discharge - Extreme low-flow discharge Q90 (90 percentiles of the FDC)	m^3/s
Timing	High-flow	Julian date of 1-day maximum discharge	day
	Low-flow	Julian date of 1-day minimum discharge	day
Duration and frequency	High-flow	Index of hydrological regime alteration in high-flow: FQ-high flow	%
	Low-flow	Index of hydrological regime alteration in low-flow: FQ-low flow	%

We further divided the long-term time series of flow metrics into three periods: NDD, LDD (low-dam development, 1993–2008), and HDD (high-dam development, 2009–2015) to further differentiate the postdam period into LDD and HDD periods before and after the operation of the second largest dam in the Mekong basin, Xiaowan, in December 2008. The LDD period consisted of four mainstream dams in the Lancang cascade and 18 dams in the tributaries (Table S1). The HDD period included additional two mainstream dams in the Lancang cascade and 38 dams in the tributaries.

2.4.2. Index of hydrological regime alteration (FQ)

We adapted the *FQ* proposed by Alcayaga et al. (2012) to assess alterations in the frequency and duration in the high-flow and low-flow seasons at stations along the lower Mekong. The general form is as follows:

$$FQ(\%) = \frac{NQ_{post}}{NQ_{pre}} \times 100 - 100 \tag{6}$$

where $FQ(\%)$ is the index of frequency alteration applied to the high-flow and low-flow conditions; NQ_{pre} and NQ_{post} are the numbers of

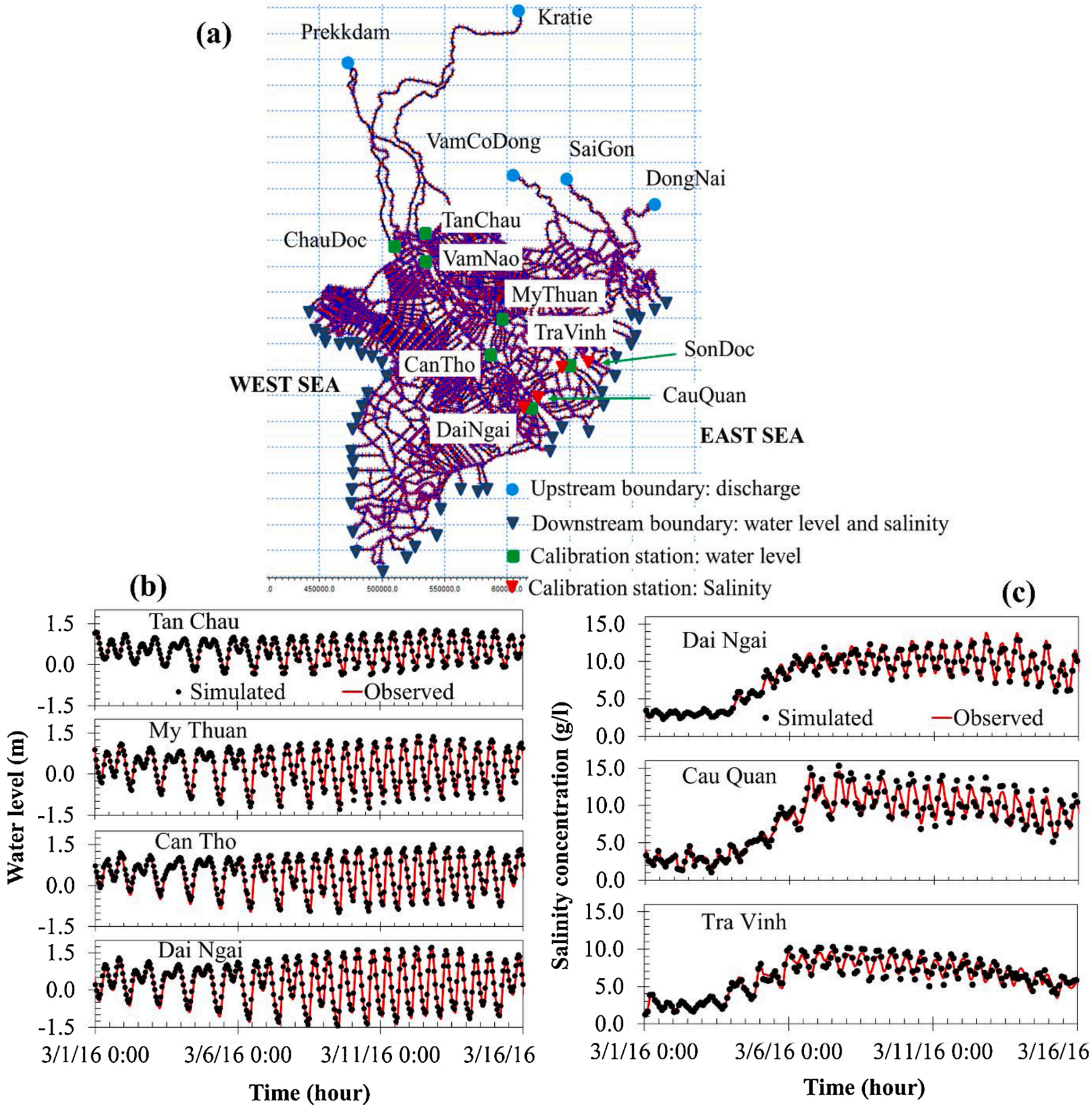

Fig. 2. (a) river network in a one-dimensional hydrodynamic and advection-dispersion model in modelling salinity intrusion in the VMD, including boundaries and validation stations. (b)-(c) comparison between simulated and observed water levels and salinity concentrations in model validation. The model was well validated.

days (duration) that have discharges exceeding the high-flow discharge or lower than the low-flow discharge in the NDD and postdam periods, respectively.

2.4.3. Statistical trend tests

The alterations of the long-term discharge, water level, precipitation, and salinity concentrations in the Mekong were examined by using the non-parametric Mann-Kendall and Pettitt tests and the slope method of Sen at the 5 % significance level ($\alpha = 0.05$). First, changes in the trend of the long-term data were detected by the Mann-Kendall test (Kendall, 1938; Mann, 1945). When trends were detected, we identified inflection points in the time series using the Pettitt test (Pettitt, 1979). Finally, the slope method of Sen (Sen, 1968) was employed to estimate the rate of change (the slope) of the data. These trend tests were performed on the annual values.

2.4.4. Indicators of hydrologic alteration (IHA)

The IHA method was used to quantify flow regime alterations from the NDD to the LDD and HDD periods. This method comprises 32 hydrologic indicators, which are categorized into five groups: 1) magnitude of monthly discharge, 2) magnitude and duration of annual extreme discharge, 3) timing of annual extreme discharge, 4) frequency and duration of high and low pulses, and 5) rate and frequency of flow changes (Richter et al., 1998). The IHA method was performed on daily discharges.

2.4.5. Flow duration curve (FDC) and frequency analysis

The FDCs were established for the NDD, LDD, and HDD periods at each station in the Mekong to quantify flow regime alterations. In each period, daily discharges were averaged and ranked in descending order. Then, daily ranked discharges, Q_i, were plotted as a function of their corresponding percent exceedance, $p_i = i/(n+1)$, where i is the rank, and n is the total number of days.

In quantifying the changes in the magnitude of annual extreme discharges (maximum and minimum) under different occurrence frequencies, flow frequency analysis was employed. First, long-term discharges were ranked in descending order. The probabilities associated with the ranked values were then computed using the Hazen equation (Bartkes et al., 2016). Finally, the predicted probabilities were estimated using the Pearson Type III probability distribution and fitted by the method of moments, as proposed by USGS (1982).

2.4.6. Distinguishing effects of climate from anthropogenic factors on flow regime alterations

The applied methods in this study are able to quantify the altered flow regimes in the postdam (i.e., LDD and HDD) period. Such alterations are driven by both natural (e.g., climate change/variability: precipitation is a proximity) and anthropogenic (e.g., dams and irrigation) factors. To distinguish effects of the latter from the former, changes in the flow regimes were first compared to changes in the precipitation. When the flow and precipitation change in different ways, anthropogenic factors likely control the flow regime alterations. We further investigate water demands for irrigation spatially and seasonally to distinguish effects of dams and irrigation. For instance, if the low-flow discharge increased, the effect of irrigation would be negligible because it consumes water causing discharge reduction.

2.4.7. Semi two-dimensional hydrodynamic and advection-dispersion model

The Mike 11 hydrodynamic modelling software developed by the Danish Hydraulic Institute was used to simulate salinity intrusion in the VMD by using the hydrodynamic and advection-dispersion modules. Adopted from Mai et al. (2018), the VMD model is developed in a semi two-dimensional fashion as it is one dimension in the river channels and quasi two dimension in the floodplains by implementing detailed network of rice field compartments as linked channels joining with the main channels. The model encompassed five upstream boundaries using hourly discharge and zero salinity and 59 downstream boundaries using hourly water level and odd hourly salinity concentration (Fig. 2a). The model consisted of 2089 branches with over 20,734 points and more than 330 control structures for irrigation and salinity control. The model was established using the up-to-date hydrologic, topographic, and bathymetric data provided by the Southern Institute of Water Resources Research, Vietnam.

The model was validated using the data measured in 2016. We used six water level stations, i.e., Tan Chau, Chau Doc, My Thuan, Can Tho, Dai Ngai, and Tra Vinh, to validate the hydrodynamic module and three salinity stations, i.e., Dai Ngai, Cau Quan, and Tra Vinh, to validate the advection-dispersion module. The accuracy of the numerical results was evaluated by the coefficient of determination (R^2) and the Nash-Sutcliffe coefficient (E_f) (McCuen et al., 2006). Fig. 2b–c show a good agreement between the simulated and observed data with $R^2 > 0.85$ and $E_f > 0.85$ in the hydrodynamics module and R^2 ranging from 0.73 to 0.81 in the advection-dispersion module.

We then established three scenarios to investigate the effect of constructing sluice gates along the main rivers on salinity intrusion in the VMD. The baseline scenario used discharges, water levels, salinity concentrations, and number of sluice gates in the drought event of 2016. The remaining two scenarios used the respective data measured in the drought events of 1998 and 2005. The number of sluice gates constructed along the branches of the Tien and Hau rivers from 1998 to 2005 was 58 and was increased by an additional 11 from 2005 to 2016. In investigating the effectiveness of dam operation on mitigating salinity intrusion into the VMD, we established the fourth scenario by shifting the upstream boundary discharges at Kratie in March-April 2016 backward by one month. This scenario was stemmed from the emergency water release by dams in the upper Mekong basin in March-April 2016 to fight salinity intrusion in the VMD (Mai et al., 2018). Table 3 summarizes all scenarios of the model.

3. Results

3.1. Spatiotemporal variations in precipitation in the Mekong basin

The precipitation in the Mekong basin varies spatially (Fig. 3a). Tributaries in the left bank in Laos and the Mekong delta in Cambodia and Vietnam have more intensive precipitation than other parts in the basin. There was no statistically significant trends in the annual, low-flow season, and high-flow season precipitation in the Mekong basin (Fig. 3d–f) from 1980 to 2015 by Mann-Kendall test, although slight decreases were estimated. The annual precipitation in the upper and entire Mekong basin was less variable from the NDD to the LDD and HDD periods (Fig. 3b–c and Table 4). The mean low-flow season precipitation increased slightly from the NDD to the LDD periods but decreased substantially in the HDD period in both upper and entire Mekong basin. On the other hand, the mean high-flow season precipitation decreased in the LDD period but increased in the HDD period.

3.2. Impact variations of flow regime metrics along the lower Mekong

For the magnitude of the flow regime metrics, at Chiang Saen, low-flow discharges (e.g., minimum, Q90, February-April) were negatively impacted within slight to high grades during the LDD period, before becoming positively impacted during the HDD period, falling mainly within moderate to extreme grades (Fig. 4). In contrast, high-flow discharges (e.g., maximum, Q10, July-September) were positively impacted during the LDD period, mainly within moderate to extreme grades, before becoming negatively impacted during the HDD period, mainly within slight to high grades.

The impact patterns at Kratie, Tan Chau, and Chau Doc were relatively consistent, which were slightly different from those at Chiang Saen. Low-flow discharges were, in general, positively impacted throughout the LDD and HDD periods, falling within moderate to extreme grades at Kratie and high to extreme grades at Tan Chau and Chau Doc. At Tan Chau and Chau Doc, the minimum discharge has increased substantially. On the other hand, high-flow discharges changed from positive to negative grades from the LDD to the HDD period, mostly falling into slight to high grades. At all stations, the impact variations of average-flow discharges (e.g., mean, Q40, Q60) were not consistent throughout the postdam period. However, the general pattern changed from positive to negative grades around 2003.

The low-flow duration and frequency (i.e., FQ-low flow) changed from positive to negative impact grades from 2009 at Chiang Saen and from 1999 at Tan Chau and Chau Doc, while at Kratie, it was always negatively impacted. The most impacted areas were at Chiang Saen and Kratie, under highly to extremely negative grades. The high-flow duration and frequency (i.e., FQ-high flow) at Chiang Saen and Kratie changed from negative to positive grades in 2009, whereas it mostly belonged to positive grades at Tan Chau and Chau Doc, where it became extremely negatively impacted in 2014.

Although there was a slight deviation in the annual impact variations among the flow regime metrics, two obvious groups were distinguished. The high-flow discharge and frequency changed from positive to negative grades, and low-flow discharge and frequency changed from negative to positive grades around 2009. Noticeably, the changes at Kratie, Tan Chau, and Chau Doc started in 2003, and it became more obvious in 2009. These results supported the division into the NDD, LDD, and HDD periods. Such divisions coincided with the results from Mann-Kendal and Pettitt tests, which revealed that most of the flow metrics changed from increasing or decreasing in 1993 and/or 2009 (Table S3). These change years were consistent with the infilling years of mega-dams in the Lancang cascade (Table 1), e.g., the Manwan dam in 1993 and the Xiaowan and Jinghong dams in 2008.

3.3. Quantified alterations of flow regime metrics along the lower Mekong

3.3.1. Maximum and high-flow discharges

The maximum and high-flow discharges at all analyzed stations along the lower Mekong increased significantly in the LDD period from the NDD period (Tables 5 and 6 and S4 and S5; Figs. 5 and 6a). The largest increase in the maximum discharge was at Chiang Saen, by 18 %, and the increased rate decreased moving downstream. Frequency analysis showed that the maximum discharges increased at almost all exceedance probabilities (Tables S6–S9). Similarly, high-flow discharges increased by 1–16 % at Chiang Saen, 5–19 % at Kratie, 3–7 % at Tan Chau, and 5–15 % at Chau Doc (Tables 5 and 6 and S4 and S5). Moreover, the duration of the high-flow season (calculated by Eq. 6) in the LDD period at Tan Chau and Chau Doc increased by 12 % and 15 %, respectively. However, high-flow discharges at all stations decreased in both magnitude, frequency, and duration in the HDD period from the NDD period (Tables 5

Table 3
Scenarios used in the numerical model considering the effect of sluice gate construction and mitigation measures against salinity intrusion.

Scenario	Year of boundary condition (Discharge, water level, salinity, and sluice gate status)	Remark
Baseline	2016	For model validation. Number of sluice gate was 69
Scenario 2	1998	No sluice gate
Scenario 3	2005	Number of sluice gate was 58
Scenario 4	2016	For mitigation measure. The upstream boundary discharge at Kratie in March–April 2016 was shifted backward by one month

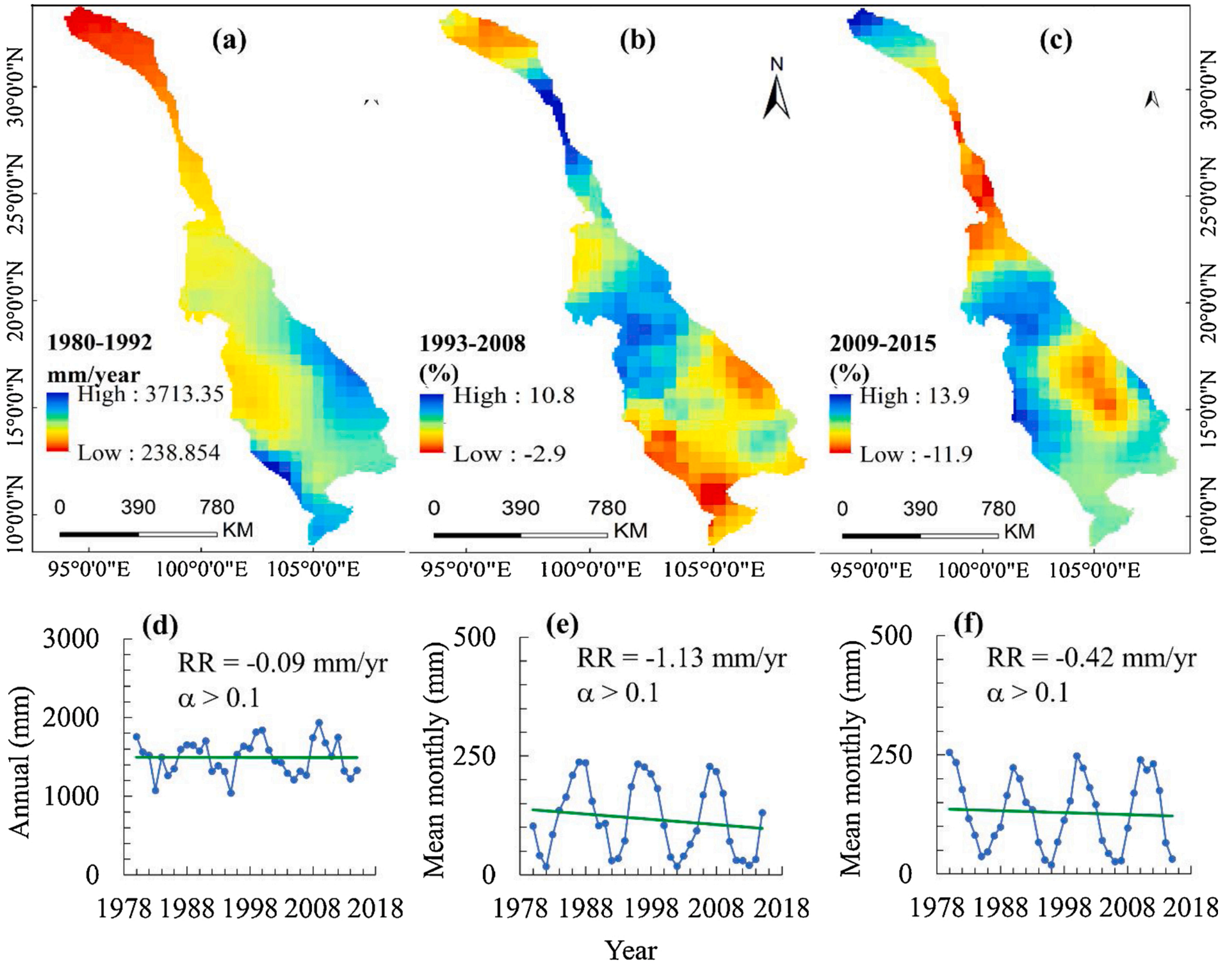

Fig. 3. Spatiotemporal variations of the precipitation in the Mekong basin. (a) mean annual precipitation in the NDD period. (b)-(c) mean annual precipitation changes in the LDD and HDD periods relative to the NDD period. (d)-(f) long-term annual, mean monthly low-flow season, and mean monthly high-flow season precipitation from 1980 to 2015. No statistically significant trends were detected. Reduced rates are the slopes of the linear regression.

Table 4
Changes in the annual, mean low-flow season, and mean high-flow season precipitation (mm) in the NDD, LDD, and HDD periods in the upper and entire Mekong basin.

Month	NDD	LDD		HDD	
	Precipitation	Precipitation	Change (%)	Precipitation	Change (%)
Upper Mekong					
Annual	898	873	−2.6	905	+0.9
Mean low-flow	76	81	+6.3	41	−45.5
Mean high-flow	87	59	−31.7	93	+6.6
Entire Mekong					
Annual	1501	1459	−2.8	1534	+2.2
Mean low-flow	125	126	+1.0	70	−44.4
Mean high-flow	144	106	−26.4	161	+12.6

Note: Change (%) = [HDD (or LDD) – NDD]/NDD *100 %. "+": increase and "-": decrease.

and 6 and S4 and S5; Figs. 5 and 6a). The reduction rates at Chiang Saen and Kratie were greater than those at Tan Chau and Chau Doc. The largest reduction rate was at Chiang Saen, by −26 %, in July. Also, the maximum discharge decreased at Chiang Saen and Kratie. For instance, the trend tests revealed that the maximum discharge decreased by a rate of −56.3 $m^3/s/yr$ at Chiang Saen ($\alpha > 0.05$).

Not only the magnitude but also the patterns of the discharge hydrographs were altered (Fig. 6a). The peak discharges at all stations

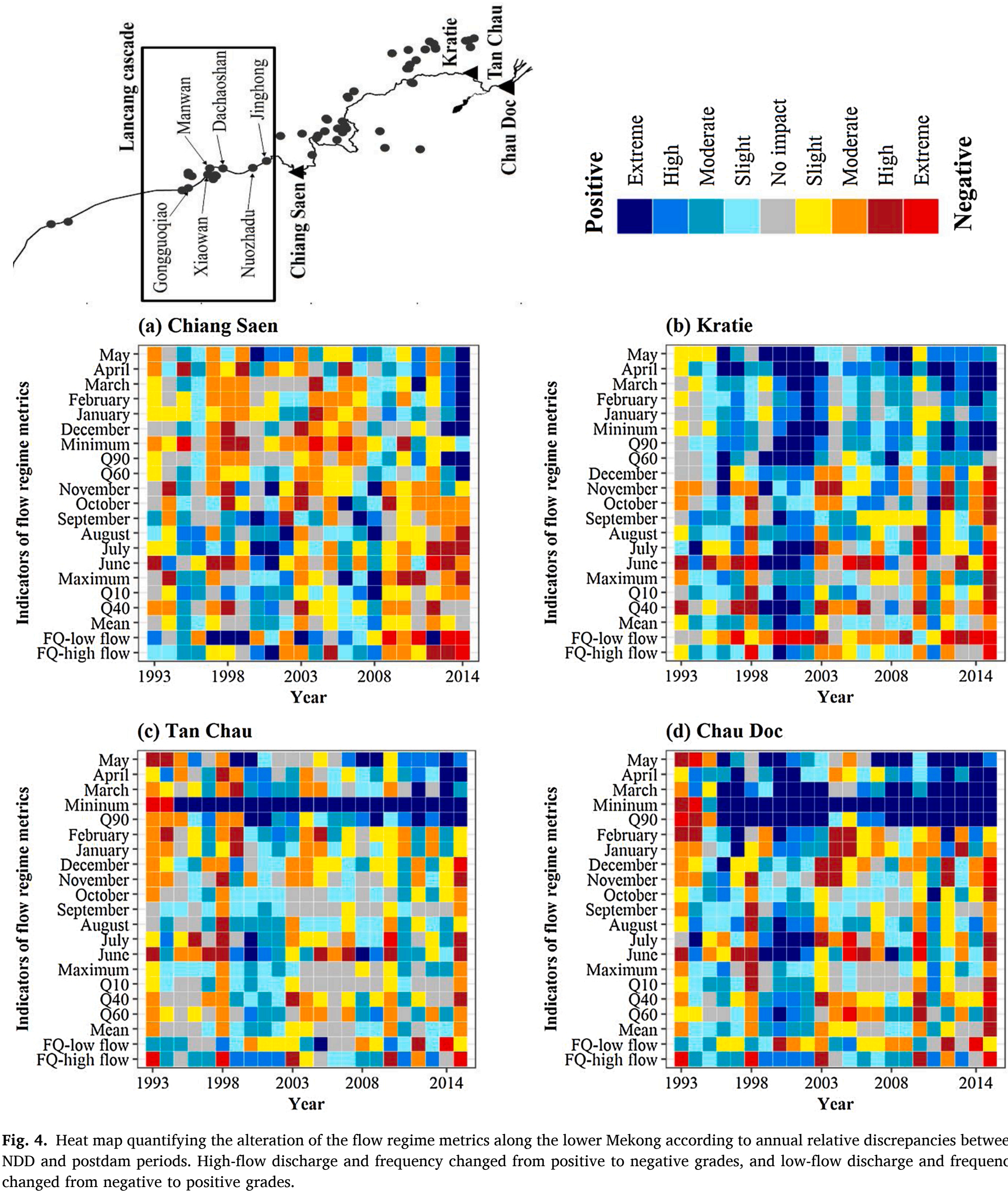

Fig. 4. Heat map quantifying the alteration of the flow regime metrics along the lower Mekong according to annual relative discrepancies between NDD and postdam periods. High-flow discharge and frequency changed from positive to negative grades, and low-flow discharge and frequency changed from negative to positive grades.

were shifted to occur later in the LDD and HDD periods than in the NDD period (Tables 5 and 6 and S4 and S5). For instance, the peak discharges were delayed on average by 6 days at Chiang Saen and 7 days at Tan Chau in the HDD period.

3.3.2. Mean and transition-flow discharges

The annual mean discharges at all four stations increased in the LDD period (1–12 %) from the NDD period. The maximum increase was at Kratie, followed by Chiang Saen. However, it decreased in the HDD period at the four stations, ranging from −2 % to −8 %, with a maximum reduction at Chiang Saen. At Chiang Saen and Kratie, the transition-flow discharges generally increased in the LDD period

Table 5
Results of the IHA analysis performed to determine discharge alterations for Chiang Saen from the NDD to the LDD and HDD periods.

Indicators	Units	NDD	LDD		HDD	
		Magnitude	Magnitude	Deviation magnitude(%)	Magnitude	Deviation magnitude(%)
January	m^3/s	1203	1095	−108(−9)	1514	311(16)
February	m^3/s	983	899	−84(−9)	1208	225(23)
March	m^3/s	882	834	−48(−5)	1229	347(39)
April	m^3/s	973	900	−73(−8)	1317	344(35)
May	m^3/s	1382	1491	109(8)	1610	228(16)
June	m^3/s	2546	2513	−33(−1)	1944	−602(−24)
July	m^3/s	4459	5125	666(15)	3316	−1143(−26)
August	m^3/s	5481	6351	870(16)	4811	−670(−12)
September	m^3/s	4959	5694	735(15)	4328	−631(−13)
October	m^3/s	3891	3911	20(1)	2992	−899(−23)
November	m^3/s	2532	2478	−54(−2)	2226	−306(−12)
December	m^3/s	1589	1525	−64(−4)	1946	357(22)
1 day minimum	m^3/s	790	592	−198(−25)	775	−15(−2)
3 day minimum	m^3/s	795	620	−175(−22)	852	57(7)
7 day minimum	m^3/s	803	654	−149(−19)	895	92(11)
30 day minimum	m^3/s	850	742	−108(−13)	1050	200(24)
90 day minimum	m^3/s	931	855	−76(−8)	1227	296(32)
1 day maximum	m^3/s	9755	11,510	1755(18)	7249	−2506(−26)
3 day maximum	m^3/s	9342	10,780	1438(15)	6714	−2628(−28)
7 day maximum	m^3/s	8472	9576	1104(13)	5964	−2508(−30)
30 day maximum	m^3/s	6416	7385	969(15)	5083	−1333(−21)
90 day maximum	m^3/s	5199	5925	726(14)	4327	−872(−17)
Date of minimum	Day	87	93	6(7)	101	14(16)
Date of maximum	Day	240	243	3(1)	246	6(3)
Low pulse count	Number	0	2.3	2.3	0.3	0.3
Low pulse duration	Day	0	4	4	11	11
High pulse count	Number	5.8	4.7	−1.1(−19)	5.3	−0.5(−9)
High pulse duration	Day	10.6	18.7	8.1(76)	6.8	−3.8(−36)
Rise rate	Number	229.3	237.2	7.9(3)	202.4	−26.9(−12)
Fall rate	Number	−128.1	−188.4	−60.3(−47)	−151.9	−23.8(−19)

and decreased in the HDD period compared to the NDD period (Fig. 6b). At Tan Chau and Chau Doc, the discharges of all months in the transition-flow season decreased significantly in the HDD period, while slight reductions in the LDD period were revealed.

3.3.3. Minimum and low-flow discharges

The minimum and low-flow discharges decreased at Chiang Saen (e.g., minimum discharge decreased by −25 %) and increased markedly at Kratie, Tan Chau, and Chau Doc in the LDD period from the NDD period (Tables 5 and 6 and S4 and S5; Figs. 5 and 6c). These trends were consistent with the frequency analysis results at all non-exceedance probabilities (Tables S10–S13). Additionally, the duration of the low-flow season increased in the LDD period, e.g., from 91 days in the NDD period to 97 days in LDD period at Tan Chau.

The minimum and low-flow discharges at all stations increased significantly in the HDD period from the NDD period (Tables 5 and 6 and S4 and S5; Figs. 5 and 6c). The increased rates of the low-flow discharge were 23–39 % at Chiang Saen, 21–62 % at Kratie, 1–38 % at Tan Chau, and 12–67 % at Chau Doc. Moreover, the duration of the low-flow season decreased significantly, e.g., from 91 days in the NDD period to 79 days in the HDD period at Tan Chau.

3.4. Long-term alterations of water level and salinity

Various indicators of water levels at Tan Chau and My Thuan (Fig. 1) in the VMD showed decreasing trends at different rates in the long-term time series (Fig. 7). Maximum and high-flow water levels experienced the most significant reduction. For instance, high-flow water levels at Tan Chau and My Thuan decreased by −17.3 mm/yr ($\alpha > 0.05$) and −5.8 mm/yr ($\alpha = 0.01$), respectively. The decreasing rate of the mean daily water level at Tan Chau (−0.02 mm/day) was greater than that at My Thuan (−0.01 mm/day). Moreover, long-term minimum and low-flow water levels at these two stations decreased as well, which may increase salinity intrusions in the VMD. For instance, the minimum water level at Tan Chau increased by 71 % in the LDD period but decreased by −51 % in the HDD period from the NDD period.

Controlling and mitigating salinity intrusions is of strategic importance to maintain and increase agricultural production in the VMD. However, long-term salinity concentrations in the VMD have sharply increased (Fig. 8a–b). Maximum salinity concentrations at Tra Vinh in the Tien river and Cau Quan in the Hau river (Fig. 1) increased with a rate of 0.23 g/l/yr ($\alpha < 0.001$) and 0.16 g/l/yr ($\alpha = 0.01$), respectively, during the period 1990–2016. Moreover, salinity intrusions were more severe in recent years than the past. For instance, the maximum salinity concentration at Cau Quan in 2016 was approximately 1.4 times (42 %) greater than that in 1998 (16.5 g/l in the former and 11.6 g/l in the later). The results of the numerical simulations showed that the extent of salinity concentrations of

Table 6
Results of the IHA analysis performed to determine discharge alterations for Kratie from the NDD to the LDD and HDD periods.

Indicators	Units	NDD	LDD		HDD	
		Magnitude	Magnitude	Deviation magnitude(%)	Magnitude	Deviation magnitude(%)
January	m^3/s	3204	3677	473(15)	3632	428(13)
February	m^3/s	2418	2817	399(17)	2920	502(21)
March	m^3/s	2000	2408	408(20)	2721	721(36)
April	m^3/s	1842	2498	656(36)	2986	1144(62)
May	m^3/s	2932	4050	1118(38)	3942	1010(34)
June	m^3/s	9882	9779	−103(−1)	7677	−2205(−22)
July	m^3/s	18,140	21,570	3430(19)	17,470	−670(−4)
August	m^3/s	31,930	36,310	4380(14)	30,990	−940(−3)
September	m^3/s	33,430	37,930	4500(13)	31,560	−1870(−6)
October	m^3/s	22,260	23,270	1010(5)	22,920	660(3)
November	m^3/s	10,580	10,990	410(4)	9282	−1298(−12)
December	m^3/s	5230	5928	698(13)	5054	−176(−3)
1 day minimum	m^3/s	1691	2094	403(24)	2379	688(41)
3 day minimum	m^3/s	1700	2114	414(24)	2407	707(42)
7 day minimum	m^3/s	1715	2147	432(25)	2448	733(43)
30 day minimum	m^3/s	1792	2269	477(27)	2598	806(45)
90 day minimum	m^3/s	2009	2514	505(25)	2858	849(42)
1 day maximum	m^3/s	44,940	47,790	2850(6)	44,960	20(0.04)
3 day maximum	m^3/s	44,520	47,520	3000(7)	44,510	−10(−0.02)
7 day maximum	m^3/s	43,350	46,690	3340(8)	43,270	−80(−0.2)
30 day maximum	m^3/s	38,480	41,340	2860(7)	35,470	−3010(−8)
90 day maximum	m^3/s	30,290	34,510	4220(14)	29,920	−370(−1)
Date of minimum	Day	107	100	−7(−7)	81	−26(−24)
Date of maximum	Day	246	246	0(0)	252	6(2)
Low pulse count	Number	1.4	2	0.6(43)	1.3	−0.1(−7)
Low pulse duration	Day	79.2	29.4	−49.8(−63)	24.8	−54.4(−69)
High pulse count	Number	3	1.4	−1.6(−53)	2.7	−0.3(−10)
High pulse duration	Day	27.3	65.8	38.5(141)	29.9	2.6(10)
Rise rate	Number	780.4	677.8	−102.6(−13)	595.5	−184.9(−24)
Fall rate	Number	−388.8	−385.6	3.2(1)	−421.1	−32.3(−8)

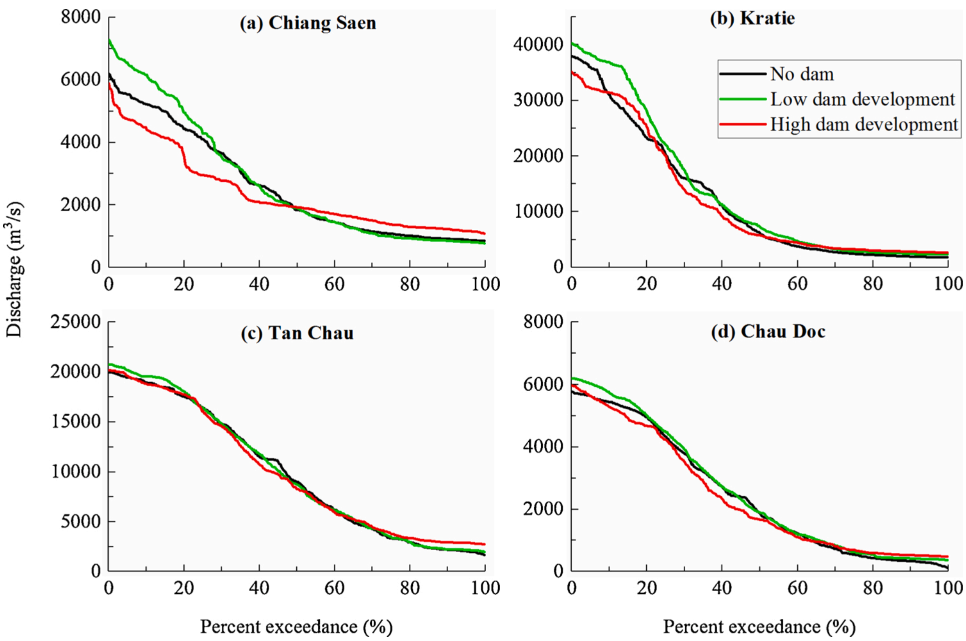

Fig. 5. Flow duration curves in the NDD, LDD, and HDD periods along the lower Mekong. High-flow discharge increased in the LDD period and decreased in the HDD period from the NDD period. Low-flow discharge increased in both LDD and HDD peridos from the NDD period.

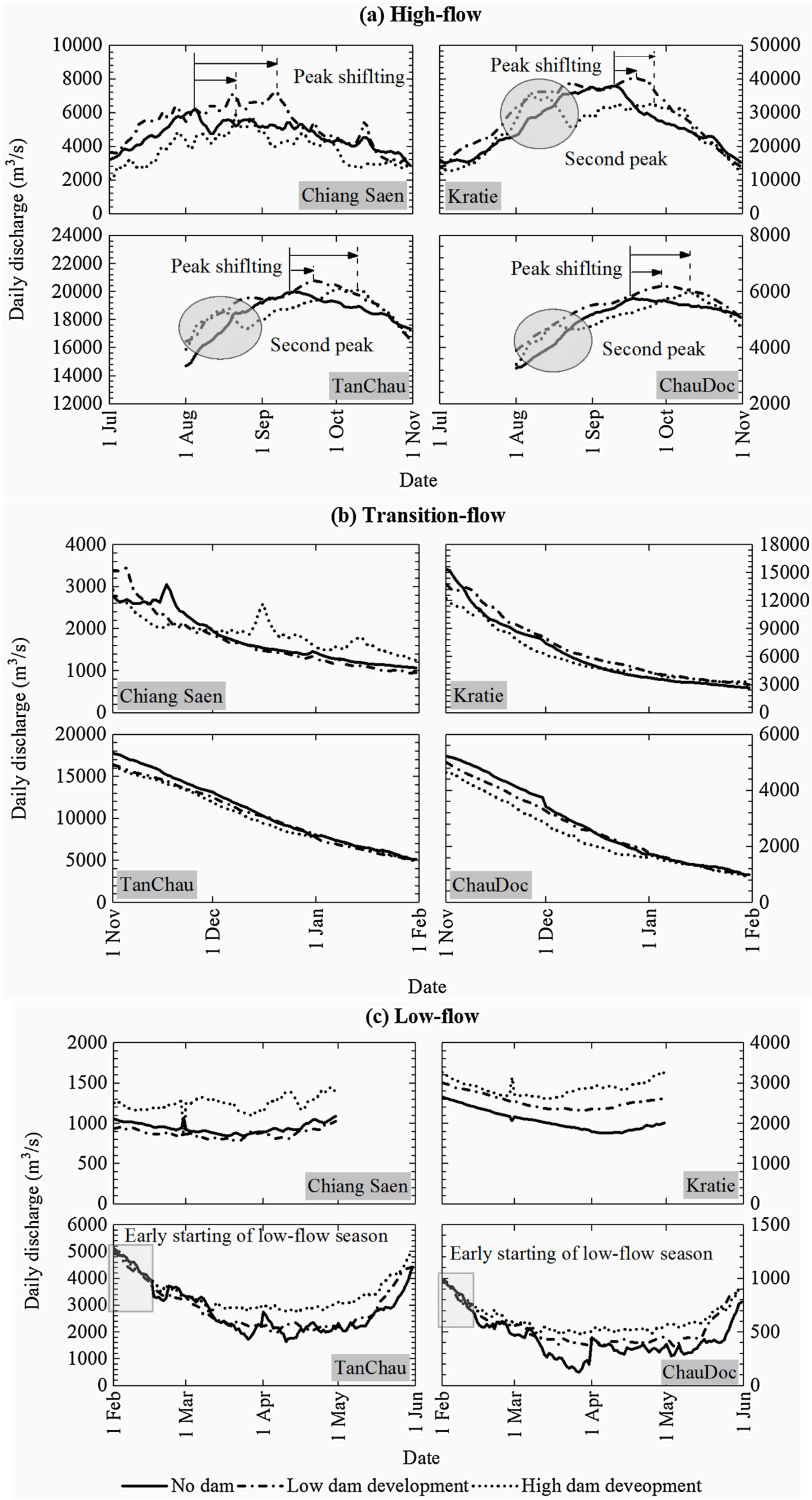

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Fig. 6. Differences of the discharge hydrographs between the NDD and LDD and HDD periods along the lower Mekong in the (a) high-flow, (b) transition-flow, and (c) low-flow seasons.

at least 4 g/l in the Hau river increased from 48 km in 1998 (in the LDD period) to 58 km in 2005 and 65 km in 2016 (both in the HDD period) (Fig. 8d). Not only the magnitude but also the intrusion pattern shifted substantially, i.e., beginning earlier in recent years than in the past (Fig. 8c). Particularly, the timing of occurrence of the maximum salinity concentration in 2016 was approximately 1−2 months earlier than that in previous years. For instance, at Cau Quan, the maximum salinity concentration occurred in February 2016, while it occurred in April 1998 and March 2010. However, if upstream dams released emergency water in February 2016 instead of in March-April (one month earlier in the fourth scenario), salinity intrusion in the VMD would be reduced by 3–17 % (Fig. 8e).

4. Discussion

The analysis results from various approaches showed substantial alterations in the flow regimes along the lower Mekong. Overall,

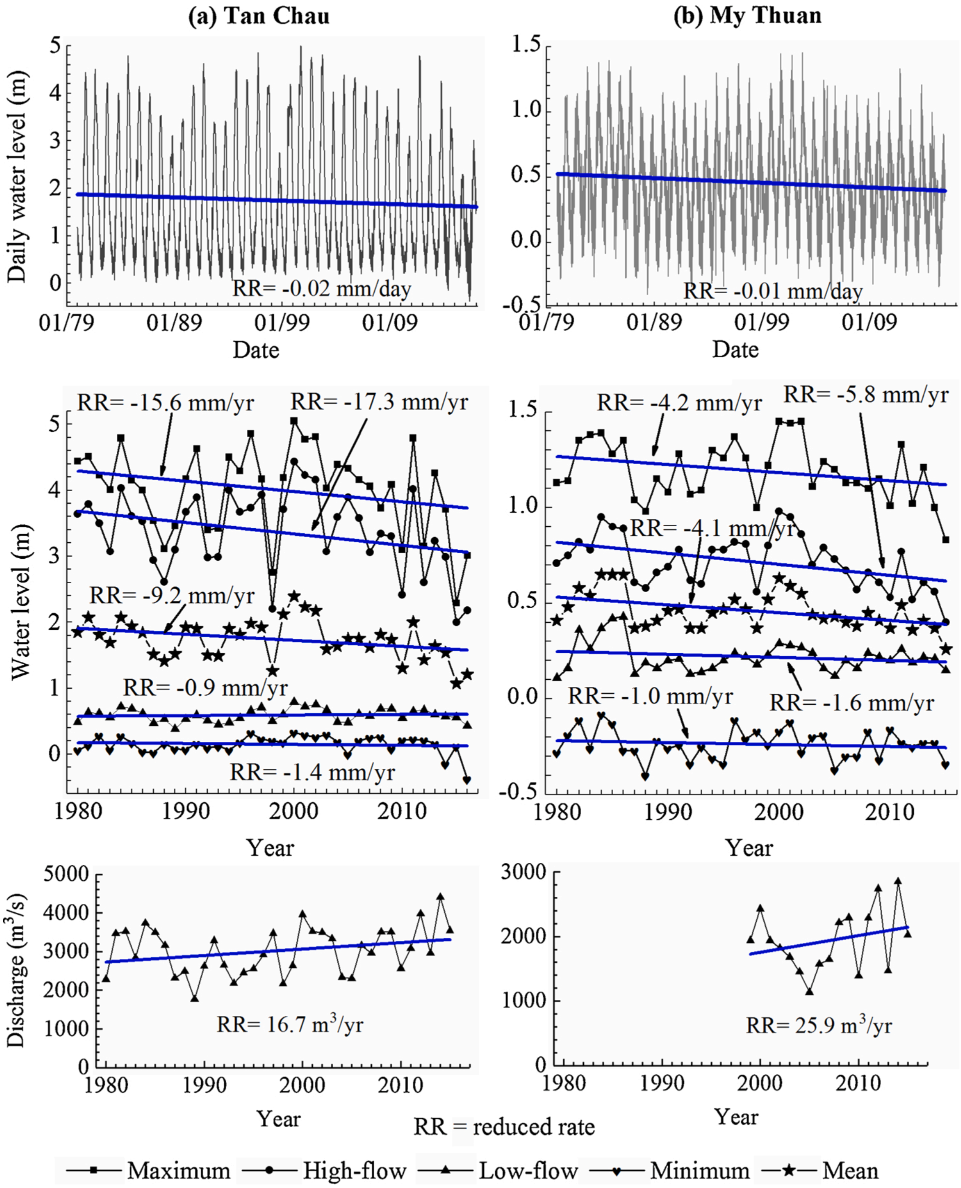

Fig. 7. Decreasing trends of various indicators of the water level at (a) Tan Chau and (b) My Thuan along the Tien river in the VMD. The low-flow discharge at these stations increased while the low-flow water level decreased due to riverbed incision. The most reductions were the maximum and high-flow water levels. Decreased/increased rates are the slopes of the linear regression.

this study shows the benefit of using the IHA indices in quantifying hydrological changes at the basin scale. These indices are useful for developing adaptation strategies for water resource management in the VMD due to salinity intrusion induced by flow regime alterations.

4.1. Drivers of flow regime alterations along the lower Mekong

4.1.1. In the LDD period

In river systems undisturbed by human activities, climate conditions are the key drivers for controlling the river flow regimes. However, the flow alteration mechanism would be more complicated if anthropogenic interventions, such as hydropower dams, were present in the river systems. Maximum and high-flow discharges at the four analyzed stations (Chiang Saen, Kratie, Tan Chau, and Chau Doc) increased in both magnitude and duration in the LDD period from the NDD period, mainly with moderately to highly positive grades (Tables 5 and 6 and S4 and S5; Figs. 4 and 5). However, the precipitation in the high-flow season decreased in the upper (−31.7 %) and entire (−26.4 %) Mekong basin (Table 4). Therefore, increases in the intensity and shifting in the timing and pattern of tropical cyclones (e.g., more concentrated over shorter time periods) may explain such discharge increases because the precipitation derived from tropical cyclones falls largely during, or just after, monsoon months when subsoil layers are already wetted or even saturated; therefore, these events are effective in forming runoff (Darby et al., 2016). Kingston et al. (2010) found an earlier occurrence of and reduced flood peak at Chiang Saen due to climate-driven factors (because they did not incorporate dams in their numerical model), which was consistent with the reduced precipitation in the high-flow season in the upper Mekong basin (Table 4) while our observed data at Chiang Saen showed a delay of and increased flood peak in the LDD period (Fig. 6a). This discrepancy shows a signal

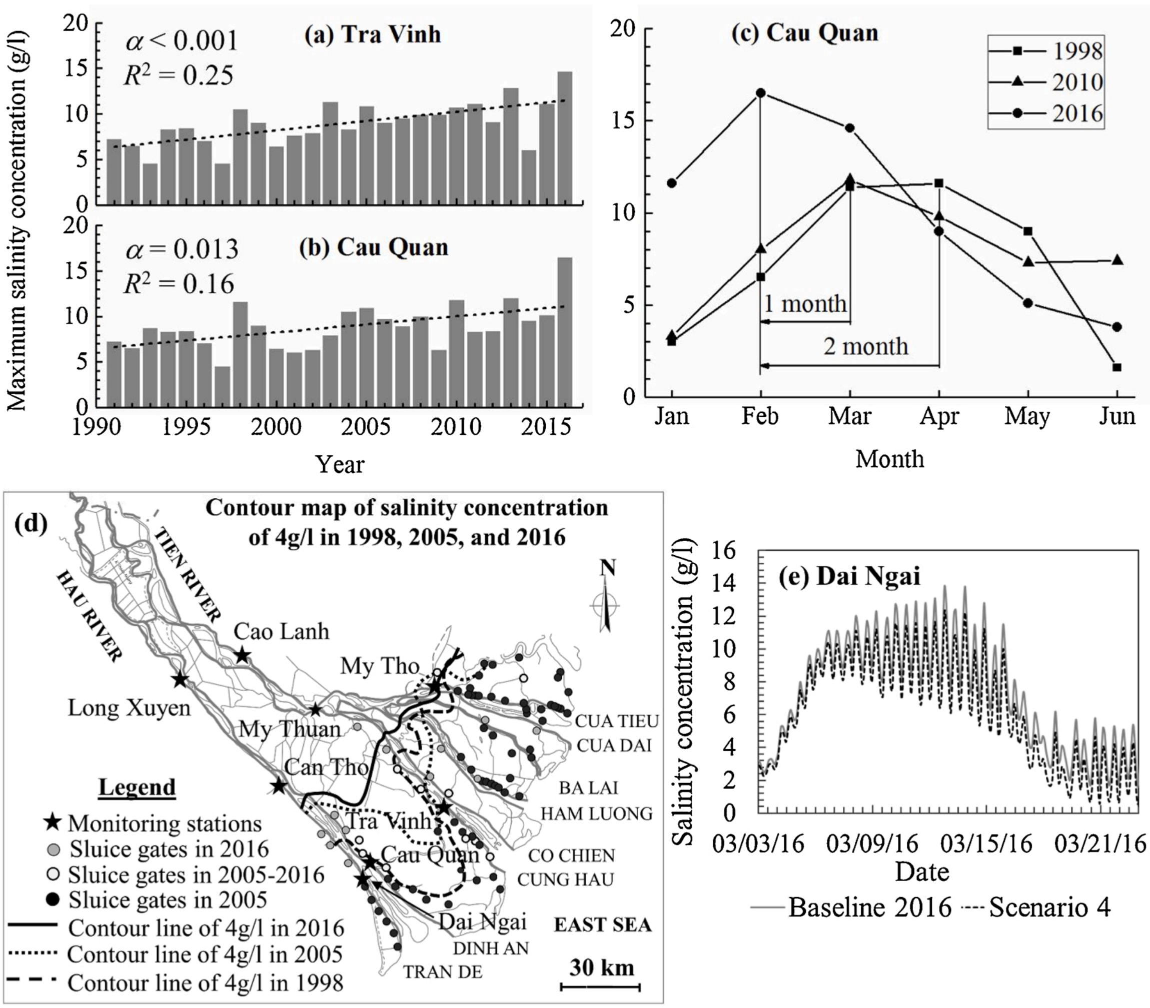

Fig. 8. (a)-(b) increasing trends in the annual maximum salinity concentrations at Tra Vinh and Cau Quan. (c) monthly maximum salinity concentrations at Cau Quan showing earlier salinity intrusion in recent years compared to the past by 1–2 months. (d) contour map of salinity concentration of 4 g/l of severe drought years in 1998, 2005, and 2016 in the VMD showing increasing intrusion length in recent years. (e) early emergency water release from upstream dams helps mitigate salinity intrusion in the VMD.

of dam influence. Therefore, it is more likely that hydropower dams in the Mekong basin with relatively small reservoir capacities in the LDD period (Table S1) may intensify the maximum and high-flow discharge increases through reservoir operations because tropical cyclones usually occur when reservoirs are almost or already full, and as a result dam regulators have to release a huge volume of water as fast as possible for dam safety reasons.

The minimum and low-flow discharges in the LDD period at Chiang Saen decreased in magnitude and increased in duration and frequency (Table 5; Figs. 5a and 6 c). Our results are consistent with the findings of Lu et al. (2014). However, the precipitation in the low-flow season in the upper Mekong basin increased by 6.3 % (Table 4). Kingston et al. (2010) numerically found that the low-flow discharge at Chiang Saen increased due to enhanced snowmelt (from increased temperature), increased rain: snow ratio, and changing climate (from seven global climate models). Therefore, the reduced minimum and low-flow discharges in the LDD period at Chiang Saen are likely attributed to dam operations in the Lancang cascade, which is consistent with the findings by Lu et al. (2014). This implies that dams in the LDD period modified the low-flow discharge in the Mekong more strongly than the climate-driven factors. However, the low-flow discharge at Kratie, Tan Chau, and Chau Doc in the LDD period increased (Tables 6 and S4 and S5; Figs. 5b–d and 6 c). This was likely driven by a slight increase in the precipitation (Table 4). Other drivers may also involve in altering the flow regimes in the Mekong in various magnitudes and extents, including shrinkage of glacial covers in the Tibet Plateau, reforestation/afforestation, highway construction, sand mining, and water diversion and consumption due to population growth (Lu et al., 2014).

Because hydropower dams normally release water in the dry season from stored water in the flood season, dam effect on the mean annual discharge should be minimal. Therefore, increases in the mean annual discharges at all analyzed stations are attributed to climate variability, possibly by local warming leading to increased local annual precipitation (Kingston et al., 2010). Decreased discharges in November-December in the transition-flow season at analyzed stations may be partially because of increased water demands for irrigation as irrigated land has increased by 0.57 % from 2000 to 2010 (Li et al., 2017) and dam operations.

An important finding from the aforementioned results is that hydropower dams in the upper Mekong basin were not able to reduce the maximum and high-flow discharges and increase the minimum and low-flow discharges downstream in the LDD period, which differs from the conventional functions of hydropower dams that increase the low flow and reduce the high flow.

4.1.2. In the HDD period

Wang et al. (2017) estimated striking increases in the flood peak and flood frequency at Chiang Saen after 2010 compared to the period 1975–2004 induced by climate change causing increased precipitation in the upper Mekong basin. We found a slight increase (6.6 %) in the high-flow season precipitation in the upper Mekong basin in the HDD period compared to the NDD period (Table 4). Increased flood peak and flood duration under climate change effect were also estimated by Hoanh et al. (2010). However, we estimated substantial decreases in the flood peak, flood frequency, flood duration, and high-flow discharges at Chiang Saen in the HDD period (Table 5). This indicates that dams with large reservoir capacity in the upper Mekong basin, especially the Xiaowan and Nuozhado, have reduced the flood flow significantly. It is consistent with the numerical modelling results by Wang et al. (2017). Moreover, the delay of the flood peak (Fig. 6a) is likely attributed to the operations of dams in the upper Mekong basin, especially the Lancang cascade. Therefore, dams in the upper Mekong basin have greater impacts on the flood flow than climate change in the HDD period.

Flood frequency and high-flow discharges largely decreased at Kratie, Tan Chau, and Chau Doc in the HDD period (Tables 6 and S4 and S5), which are inconsistent with the slightly increased high-flow season precipitation in the Mekong basin (Table 4). Flood peaks were delayed. Collectively, these imply that all dams in the Mekong basin cumulatively reduced flood pulses and regulated the flood flow in the lower Mekong, exceeding climate change effect. Analyzing the data from 2009 to 2016, Ha et al. (2018b) found a time lag between the discharge (at My Thuan and Can Tho) and the ENSO (El Niño Southern Oscillation) of 7–8 months with low correlation coefficients, suggesting that dams have regulated the interannual discharge changes. Moreover, diversion infrastructures, such as the Nam Theun 2 dam and extensive diversions for irrigation in the Mun-Chi basin in the north-eastern Thailand, may additionally reduce the high-flow discharges in the lower Mekong (Hecht et al., 2019).

In the HDD period, minimum and low-flow discharges at all analyzed stations increased significantly (Tables 5 and 6 and S4 and S5; Figs. 4–6c). The duration and frequency of the low-flow season decreased markedly. These are in contrast with significant decreases in the low-flow season precipitation in the upper (−45.5 %) and entire (−44.4 %) Mekong basin (Table 4). Such opposite trends are obvious signals of the effects of dam operations that release water in the dry season. These findings are in good agreement with the results of at least three prior studies (e.g., Li et al., 2017; Räsänen et al., 2012, 2017). Increasing water intake for irrigation due to expansion of agricultural lands, especially in Cambodian and Vietnamese Mekong Deltas, may reduce the low-flow discharge. However, this driver clearly has minimal effect because of substantial increases of the low-flow discharges due to dam operations. Li et al. (2017) found that dam-induced flow regime alterations in the Mekong basin far exceed the land use-induced influence.

Decreased mean annual discharges at analyzed stations which were consistent with the decreased trends at Can Tho and My Thuan (Ha et al., 2018b) may be attributed to climate variability because hydropower dams basically preserve the total water volume in reservoirs. Decreased discharges in May-July in the transition-flow season at stations along the Mekong may be attributed to early water storing by reservoirs or climate variability. Decreased discharges in November-December in the transition flow may be attributed to dam operations and increased water demands for irrigation (Li et al., 2017), especially in the Mekong delta because water demands for irrigation peak in these months when the Spring-Winter rice crop starts.

The aforementioned findings imply that existing dams in the Mekong basin in the HDD period cumulatively reduced the flood pulses and increased the low-flow discharge along the Mekong through reservoir operations, exceeding climate change effect.

4.2. Cumulative impacts on the Vietnamese Mekong Delta

There are two major concerns for the VMD related to the flow regime alterations, especially during the HDD period: reduction of the flood pulses and frequency and decrease in the low-flow water levels. Both of these have negatively changed farming practices, increased salinity intrusions, and affected livelihoods of the local people in the VMD. Flood pulses are important for the society that is dependent on fisheries and floodplain agriculture. The estimated annual economic benefit from a typical wet-season flood pulse is $8−10 billion in the lower Mekong basin, which is over a hundred times greater than the annual damages caused by the flooding, estimated at $60−70 million (Hecht et al., 2019). Reduced flood pulses might disconnect the main Mekong to its floodplains in the VMD, preventing nutrient-rich sediment from depositing on the floodplains, with negative consequences to ecosystems and agricultural production. Reduced natural fertilizer in agricultural lands due to reduced flood pulses would pose a risk on the environment because farmers tend to increase artificial fertilizer and pesticide use to maintain agricultural production. Moreover, local people, especially the poor, would be vulnerable due to potentially losing their secondary income from fisheries in the floodplains during the high-flow season because of river-floodplain disconnection. Reduction in floodplain fisheries and increased use of artificial fertilizers and pesticides in the VMD have been occurring for at least the last five years, presenting serious challenges to the Vietnamese government from the human security and the environmental aspects.

Although low-flow discharges in the VMD increased, low-flow water levels decreased (Fig. 7). This can be explained through riverbed incision. Binh et al. (2018b) found that the rate of riverbed incision was faster than the rate of water depth increase from the increased dry season discharge in the main rivers of the VMD. Riverbed incision is a consequence of reduced sediment supply from the Mekong due to reservoir sediment trapping (Kondolf et al., 2014; Kummu et al., 2010) and sand mining (Jordan et al., 2019; Kondolf et al., 2018). Binh et al. (2020) found that riverbed incision in the Tien river in 2014–2017 was approximately threefold that in 1998–2008 and upstream dams explained for approximately 85 % of riverbed incision compared to 15 % from sand mining. Additionally, water abstraction for irrigation of agricultural lands, especially in the Cambodian and Vietnamese Mekong Deltas, may reduce the low-flow discharge. However, this driver clearly has minimal effect because the low-flow discharge increased significantly. It means water abstractions are likely not responsible for decreased low-flow water level.

Reductions in the low-flow water levels pose two critical problems. The first problem is the difficulty in obtaining irrigation freshwater, especially during the winter-spring crop which is the most productive and important among the three rice crops in the VMD. As a result pumping is used to lift water for irrigation as an alternative, which ultimately reduce the income of farmers. Second, the reduction in the low-flow water levels is likely one of the causes of significantly increased salinity intrusions in the VMD (Fig. 8a–b), in which the frequency of extreme salinity intrusions has been greater in recent years than in the past (Mai et al., 2018). Eslami et al. (2019) found that riverbed incision is one of the main causes of increased salinity intrusion in the VMD recently, possibly because of reduction of the water surface gradient between rivers and seas. Reduced river to sea gradient means that sea water can reach further upstream in the river during the high tide. Moreover, increasing the number of sluice gates along the main rivers was estimated to increase the length of salinity intrusion (Fig. 8d) due to reduced buffering zones.

4.3. Proposed strategies for sustainable development of the Mekong basin

Following the flow regime alterations identified in our analyses, we proposed a conceptual framework and actions (Fig. 9) to enhance sustainable development of the Mekong basin by reducing adverse impacts of the alterations. It requires keeping the main river relatively free from human interventions to maintain healthy flow and sediment regimes. Adequate supply of quality water and environmental flow from the upper and middle Mekong basins could support people's livelihoods, farming practices, and the survival of ecosystems in downstream reaches. Maintaining forest cover and restricting water diversion to other basins could mitigate extreme floods and droughts. In extreme events, reservoir operation rules should be modified to support downstream regions, which may minimize the transboundary impacts. In the Mekong delta, proactive preparedness to cope with extreme events, as the extreme flood in 2000 and drought in 2016, is prerequisite for the long-term development, which requires improving monitoring system and sharing data among countries. Importantly, strategic collaboration among riparian countries and different geographical regions is crucial to share the benefits from the Mekong.

An increase in the magnitude and frequency of floods in the LDD period, especially since an extreme flood in 2000, has forced enhanced construction of large-scale high-dike systems in the VMD. Such high-dike systems not only protect the people from flooding but also extensively convert double to triple rice crops in the VMD, which helps increase the people's income. However, under reduced flood pulses and frequency in the HDD period, high-dike systems have become barriers to isolate fine sediment from depositing into the floodplains, thus posing various social-environmental problems. Negative impacts of high-dike systems were extensively discussed in Tran et al. (2018); Triet et al. (2017); Dang et al. (2016). Therefore, flood control in recent years may not need such costly high-dike systems; instead, low-dike rings are preferable to receive flood water, which contains fine sediment (Tran et al., 2018). Cultivating lands inside existing high-dike systems should be converted from triple to double crops by permanently or periodically opening sluice gates under existing high-dikes (e.g., every 3 or 5 years). This action would recover soil properties, flush out contaminants, support wetland ecosystems, and provide more retention capacity for flood control in cities.

Critical concerns of salinity intrusion management in the VMD are to determine the quantity and location of salinity control sluice gates, which have been increasingly built and planned along the Tien and Hau rivers over the last decade. In the Hau river, for example, in response to increasing salinity intrusion, the Vietnamese government had built 11 sluice gates in 1998–2005 and an additional three in 2005–2016 from a limited number before 1998; consequently, together with the reduced low-flow water level and riverbed incision (Eslami et al., 2019), the salinity intrusion length in 2016 increased by 21 km from that in 1998 (Fig. 8d). An additional five sluice

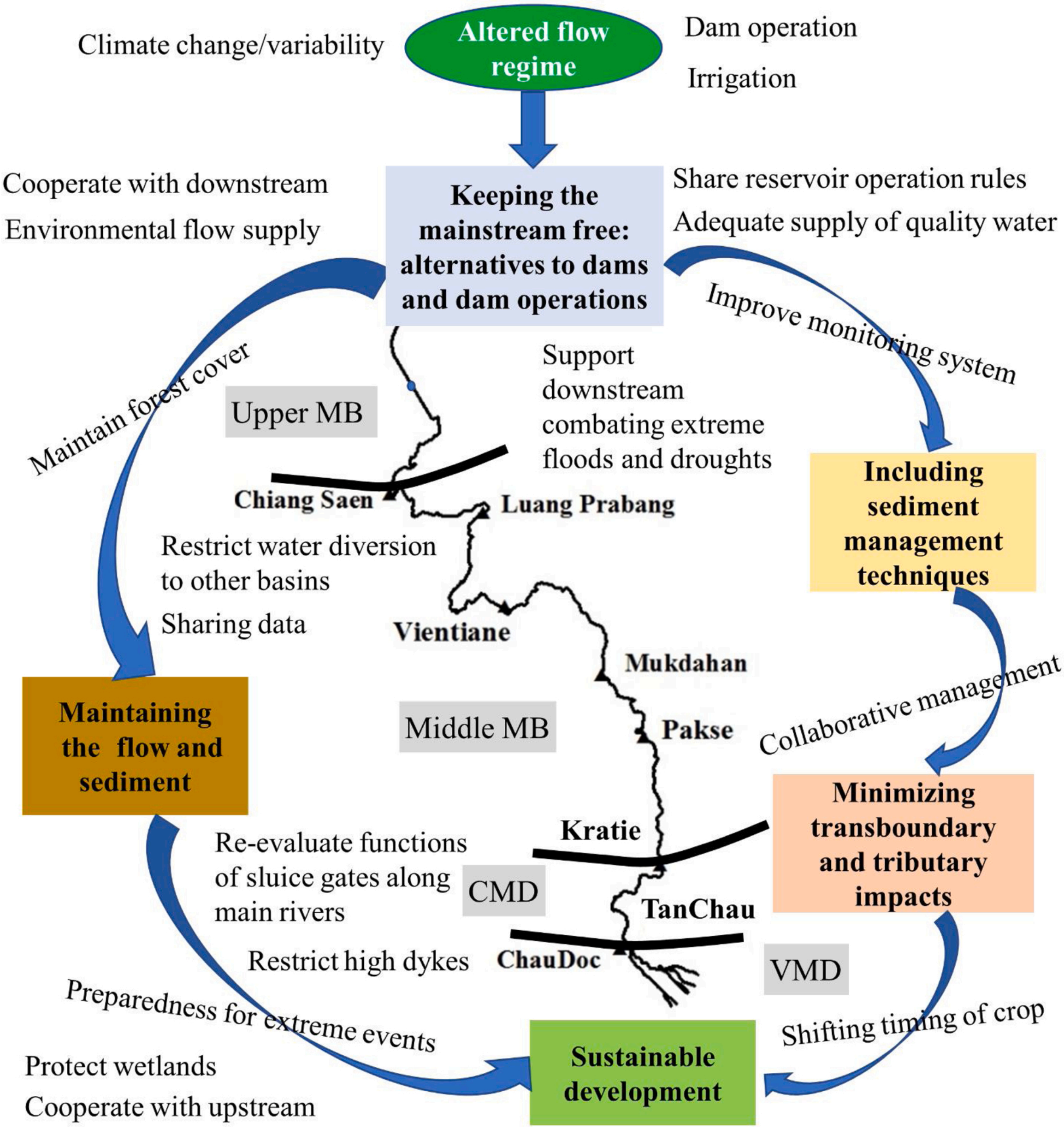

Fig. 9. Proposed framework and actions for sustainable development of the Mekong basin (MB), which requires maintaining the pristine status quo of the river. Collaboration among riparian countries and different geographical regions is crucial to share the benefits of the river. CMD: Cambodian Mekong Delta.

gates are under construction, and many are planned in the Hau river (locations are shown in Fig. 8d). When such sluice gates are completed, the salinity intrusion length in the Hau river may increase more significantly. The situation is the same in other branches of the Tien river. Therefore, we propose that building new salinity control structures along the main rivers in the VMD should be based on comprehensive assessment of the location and operation routines. Re-evaluation of existing structures is needed, which should pay special attention to clarifying the relation between recently increased sluice gate construction and the increased salinity intrusion length. In this regard, early emergency water release from upstream dams may partly reduce salinity intrusion in the VMD (Fig. 8e). Shifting the land use from agriculture to aquaculture in areas intruded by saltwater may be an effective alternative to increase income and to adapt to new flow regime conditions. Ca Mau Province is a good model of such land use change. However, aquaculture farming practices must be friendly to the environment and ecosystems. Finally, water resource management should be investigated over a long period and implemented at the delta scale but not provincial or local scales, and the results of this research is a promising reference for such management.

5. Conclusions and recommendations

In this research, we, for the first time, investigated flow regime alterations in the entire lower Mekong (from Chiang Saen to the VMD) during a 36-year period by analyzing in detail the discharges, water levels, salinity concentrations, and precipitation and discussed comprehensively the drivers of such alterations. Various analytical methods and a semi two-dimensional numerical model were used. The suitability of the existing hydraulic structures for flood control (i.e., low-dike and high-dike systems) and salinity intrusion control (i.e., sluice gates) were addressed, and some associated management policies were proposed. One of the important contributions of our study is providing evidence-based historical changes of the hydrology in the VMD which serves as an important reference for future preparedness and adaptive strategies for sustainable development of the delta. Main conclusions are:

The flow regime alterations in the HDD period are more pronounced than in the LDD period, compared to the NDD period, based on most of the indicators analyzed. Some flow regime alterations observed in the LDD period maybe attributed to the inter-annual climatic variability and changes in the tropical cyclones than the effects of reservoir operation. Hydropower dams in the LDD period with relatively small reservoir capacity (Table S1) were seemed unable to reduce the maximum and high-flow discharges and increase the minimum and low-flow discharges downstream. However, in the HDD period the existing dams in the Mekong basin seemed to have cumulatively reduced the flood pulses and frequency and increased the low-flow discharge along the entire Mekong through reservoir operations, exceeding climate change effect.

Furthermore, in the recent years water levels in the low-flow season in the VMD have decreased, possibly because of increased riverbed incision resulted from reduced sediment supply and increased sand mining. Such reduced water level together with increased construction of sluice gates seemed to have increased salinity intrusion in the VMD which may be partly reduced by early emergency water release from upstream dams.

The sustainability of the VMD requires comprehensive revision of the functioning of sluice gates and high dyke systems before building more. Any stakeholder's decisions related to water resources issues should be based on long-term flow regime alterations, and the results from this paper are a promising reference. Additionally, water resource management should be investigated over a long period and implemented at the delta scale instead of provincial or local scales.

An integrated water resource management strategy in the Mekong basin that is collaboratively designed and adopted by all riparian countries would enhance the sustainability of the river ecosystem and protection of the shared benefits provided by the river. Proactive preparedness to cope with extreme events is prerequisite for the basin sustainable development, which requires improving the monitoring system and sharing data among countries.

CRediT authorship contribution statement

Doan Van Binh: Conceptualization, Data curation, Formal analysis, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Sameh A. Kantoush:** Conceptualization, Funding acquisition, Methodology, Supervision, Writing - review & editing. **Mohamed Saber:** Data curation, Formal analysis, Resources, Writing - review & editing. **Nguyen Phuong Mai:** Data curation, Methodology, Resources, Software, Validation, Writing - review & editing. **Shreedhar Maskey:** Writing - review & editing. **Dang Tuan Phong:** Data curation, Writing - review & editing. **Tetsuya Sumi:** Funding acquisition, Project administration, Supervision, Writing - review & editing.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2020.100742.

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